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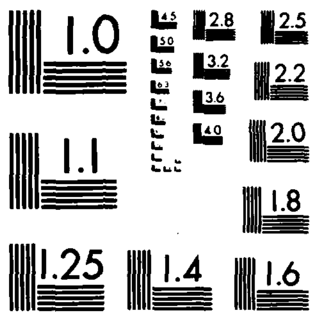

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INTRODUCING SPECIFIC KNOWLEDGE DOMAINS INTO BASIC SKILLS INSTRUCTION: FROM GENERALIZED POWERS TO SPECIFIED KNOWLEDGE

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May 1984

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AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235

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This paper has been reviewed and is approved for publication.

NANCY GUINN, Technical Director
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Chief, Manpower and Personnel Division

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This paper explores a knowledge-based approach to basic skills instruction that embodies recent advances in understanding expert human performance in complex subject-matter domains. The skills of interest are those required for apprenticeship proficiency by Air Force enlisted personnel in complex, technology-laden workplaces. Toward that end, basic job skills are being treated in this effort as the core knowledge and thinking processes that enable the first-enlistment airman to maximize on-the-job learning and proficiency and to begin progressing to skilled levels of expertise. With this conceptualization of basic skills, the role of knowledge in skilled performance is viewed as an important companion to the more traditional "powers" of reading and computing. In tandem, knowledge and powers provide a rich basis for an explication of the learning processes that enable the progression from novice to expert. Empirical support is presented which describes ways in which novices differ from experts in their knowledge structures and approaches to problem solving in complex domains, such as physics and electronics. In addition, this paper briefly describes the application of the expert-novice model in the initial months of a research and development program, where early results suggest the importance of core knowledge in the two specialties being studied. Finally, theoretical as well as empirical support for instruction of basic skills based on cognitive theory is presented.

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Introducing Specific Knowledge Domains into Basic Skills Instruction: From Generalized Powers to Specified Knowledge

INTRODUCTION

Basic skills instructional programs have traditionally adopted a power-based approach to skill enhancement, the premise being that improved performance on intellectual tasks is primarily a function of improved generalized "powers," such as reading, writing, and computing. Such a power-based strategy also characterized early endeavors in artificial intelligence (AI) where attempts to model human capabilities focused on generalized increases in computational power, or pure problem-solving techniques. As more has been learned about the properties of expert human performance -- particularly in complex subject-matter domains -- the trend in AI has shifted to knowledge-based strategies where the organization and structure of knowledge are recognized as critical components of expertise. With this orientation, improved performance on intellectual tasks is viewed to be a function not only of enhanced processing capabilities but also of enriched data bases -- or well-integrated, highly organized structures of information and procedures. A long-term research and development (R&D) effort recently undertaken by the Air Force treats the measurement and training of basic job skills using such a knowledge-based approach, thus providing a basic skills analog to the AI shift from "power" to "knowledge" emphases. The rationale for this shift is presented in this paper along with a general discussion of selected features of the instructional program that is expected to result from the conduct of the R&D.

SKILLS IN THE HIGH-TECHNOLOGY WORKPLACE

The basic skills that underpin successful job performance are by definition linked to a particular subject-matter domain and workplace. For the Air Force, as well as for the workforce in general, requisite, domain-specific skills are influenced by a variety of factors, one of which is technology. Because of the proliferation of high-technology weapon systems and equipment in Air Force workplaces, getting the job done depends more and more upon young airmen being able to interface with diverse high-tech systems. A critically important question thus becomes, "What are the fundamental skills needed in order to optimize the probability of success in that interface?" There is presently not a very complete answer to that question -- and both sides of the issue have been argued; i.e., that high-tech systems both reduce and increase the human performance load. Demands on the labor market make concerns about filling high-tech jobs even graver. All the armed services face the certainty of shrinking and otherwise changing pools of military eligibles, as promised by demographic and census data. Fluctuations in the quality of enlistees' scientific and mathematics scholastic preparation are anticipated changes of particular concern to top officials in the Air Force who have warned of scientific illiteracy in workplaces that are swelling with advanced technology (Orr, 1983). Concisely stated, the workplace is changing, and there is reason to believe that the new demands may exceed the labor market supply in both a qualitative and quantitative sense.

One way of characterizing the changing context of Air Force workplaces, as well as predicting the job context of the future, is to view the pervasive technological influences as increased demands for information and knowledge processing. It is a phenomenon of our industrialized times that manual tasks requiring observable, behavioral skills for execution are being replaced by tasks involving the collecting, processing, transmitting, and applying of information. These are mental tasks requiring skills that are, by and large, not observable. Paralleling this transformation in work skills, there is a vigorous theoretical force presently dominating psychological science -- modern cognitive psychology. As the study of how people mentally represent and process information, cognitive psychology offers promising models for explaining how individuals gain proficiency in the kinds of intellectual tasks that are abounding in the workplace. A key characteristic of these models is the emphasis on two important components of task performance: namely, the knowledge content or knowledge structures required to perform the task plus the processes by which that knowledge is organized, remembered, and utilized. The Air Force investigation into basic job skills has adopted these performance concepts from cognitive psychology to frame a program of research that is knowledge as well as power based. In this effort, basic job skills are defined as the fundamental core knowledge and the ways of using this knowledge that enable the first-enlistment airman to perform proficiently and to begin progressing to skilled levels of expertise. Proficiency in the first enlistment is judged to be a function of how well the airman learns from on-the-job experience; therefore, basic job skills are the knowledge and processes needed to maximize on-the-job learning. They can be considered readiness skills.

Tenets of cognitive psychology suggest that a critical aspect of readiness to learn, especially where complex systems are involved, is the availability of initial, useful conceptions of the system to be encountered and the tasks to be performed so that further understanding can be constructed. It is expected that the Air Force basic job skills training system that is ultimately developed will include instruction in the fundamental job/system conceptions that are considered necessary for the airman to profit from actual work experiences and maximize on-the-job learning. Why are these conceptions considered so important and how is it that they qualify as subject matter for a basic skills training program? The answers are theoretical, empirical, and practical in nature.

To treat the practical aspects first, Air Force training managers, as well as their counterparts in industry, need better information regarding the skills and knowledge required of apprentices in jobs where much of the work has become automated. Decision makers need to know to what extent it is in fact tenable to assume that the "smart machine" reduces the human performance load and thereby decreases the level of talent and training needed for the operator to perform satisfactorily. Air Force training programs in electronics, for example, have undergone some quite drastic changes recently as attempts have been made to seek the level and type of training really necessary, given the automated nature of many new electronic systems. Changes have particularly affected portions of the curriculum in initial skill training previously devoted to electronics principles, the rationale being that the Air Force electronics technician, to do the job, no longer needs in-depth knowledge about basic electrical/electronics theory. This position is equivocal, however, and, in fact, the length of training time devoted to principles of electronics has been adjusted in both directions in recent

years. A defensible resolution of the electronics training dilemma and others like it would be possible if more were known about what it actually takes to perform satisfactorily and maximize learning during apprenticeship, both in terms of core knowledge requirements and problem-solving skills. Useful, functional conceptions of electronics systems that facilitate on-the-job learning may turn out to be integral components of requisite apprenticeship skills, even if well-entrenched theoretical principles are not needed for competency at this level. The importance of such conceptions is one hypothesis being investigated in the early stages of the Air Force basic job skills R&D program. This is a reasonable hypothesis, given that empirical studies conducted to explicate competent performance of complex tasks in semantically rich domains, such as physics and electronics, have consistently demonstrated the powerfulness of such conceptions, or mental models, in differentiating expert from novice performance.

THE ROLE OF KNOWLEDGE IN EXPERT PERFORMANCE

Empirical support for the importance of initial job/task conceptions has been provided by various independent investigators who have reported common differences in the ways novices, as opposed to experts, "think about" complex systems and approach problems in complex domains. The differences concern the structure and quality of the knowledge that is brought to bear. Novices typically perform in ways that suggest severe limitations in the usefulness of their knowledge structures, or schemata, as theories to explain and predict the workings of the world. Schemata can in fact be thought of as internal theoretical models or explanations that an individual draws upon when novel situations are encountered. Such theories provide the basis for representing particular problems and inferencing beyond the givens in problem statements. The way a problem is represented, it has been argued, determines the soundness of further reasoning (Glaser, 1983). In their approaches to solving physics problems, for example, novices used what have been called naive problem representations (Larkin, 1983), naive in the sense that problems were thought about in terms of the concrete, physical elements involved (e.g., pulleys, springs, blocks). Similarly, in categorizing physics problems, novices made groupings based on physical or surface features and likewise identified literal objects and terms as the features they used in selecting basic solution methods (Chi, Feltovich, & Glaser, 1981). In electronics, physical features again prevailed as novices used the spatial proximity of the elements in circuit diagrams when tasked with reconstructing symbolic diagrams (Egan & Schwartz, 1979), and they showed consistent patterns in their erroneous problem-solving strategies that suggested only surface-level, disintegrated knowledge about electrical circuitry and current (Riley, Bee, & Mokwa, 1981). In each instance, one salient characteristic of the novice's performance was the dependence on concrete, observable problem features. Novices thought about the problems in terms of how they looked, in terms of observable real-world objects. The internal theoretical models they were drawing upon to solve problems appeared to be limited to facts about observable properties.

By contrast, in these same investigations, experts provided representations that extended beyond real-world entities to include unobservable forces corresponding to physical laws (Larkin, 1983). Specifically, they categorized physics problems according to the major physics principle governing the particular solution, and likewise in identifying features leading to basic solution methods, they cited the specific states and

conditions of the physical situation (Chi et al., 1981). To illustrate, the experts would represent a problem in terms of Newton's Second Law, for example, whereas novices would see it as an inclined plane problem. Consistent with this trend, electronics experts reconstructed symbolic drawings of circuit diagrams using the functional nature of the diagrams, not spatial proximity (Egan & Schwartz, 1979), and computer simulation models built with capabilities to solve a wide range of electronics problems possessed integrated representations of electrical circuit relations and procedures as opposed to isolated pieces of superficial knowledge (Riley et al., 1981). In general, the experts' models had more functional properties, and the experts were thereby able to represent problems in terms of the major underlying principles because they understood the explicit conditions under which the principles would be applicable (Chi, Glaser, & Rees, 1982). Simply put, experts thought about problems in terms of how systems worked and how physical forces behaved, as opposed to focusing on observable features of the problem situation. Their knowledge structures appeared to be deep, integrated, and hierarchically organized, thus providing them the basis for practical theories and efficient search capabilities in diverse problem-solving situations.

Further work has revealed additional characteristics of novice conceptions that have important implications for instruction. In addition to being shallow and not well integrated, the initial conceptions formed by the novice often contain profound errors, errors that strongly affect the assimilation of new information in the domain (Gentner & Gentner, 1983). Pedagogically, then, it can be very useful to understand the nature of the learner's misconceptions as a means of explaining why particular mistakes are being made. Diagnostic models aimed at this objective have been successfully developed and applied to enhance mathematical skills, among others (Brown & Burton, 1978).

The importance of knowledge quality and structure in explaining competent performance is thus being established rather convincingly by the expert-novice line of inquiry. Given that the structure of knowledge has been shown to differentiate experts from novices reliably and given that the level and type of knowledge needed for technologically sophisticated jobs continue to be a source of concern in both the public and private sectors, it seems useful to consider core knowledge requirements in an examination of basic job skills. For these reasons, the Air Force basic skills R&D program has been designed with a knowledge-based emphasis to complement the traditional power-based approach. In that way the important questions of "What do apprentices really need to know?" and "How is their knowledge activated?" can be addressed systematically and empirically. Moreover, it becomes possible to gain useful information to answer various adjunct questions, such as the following: What mental models and metaphors do competent performers use and how might their successful approaches be incorporated into basic job skills training programs? What common misconceptions do the less competent performers hold? What are the job-specific conceptions that are salient at various stages of the first enlistment as the airman attempts to make the transition from "novice-novice" to "expert-novice"? How might on-the-job basic skills instruction capitalize on this developmental process by providing conceptually oriented instruction at key intervals during the first enlistment?

APPLICATION OF THE EXPERT-NOVICE MODEL

In the initial 6 months of the Air Force R&D program, the first steps were taken to compile the indices needed to evaluate the feasibility of adopting the kind of expert-novice information processing approach just described in a large-scale effort to measure and train basic job skills. Preliminary applications of standard analytic techniques typically used in expert-novice studies to explicate knowledge structures have been largely successful. At this time, the data are quite meager, but one trend merits premature reporting because of its promise to provide clear replication of differential expert-novice mental models in complex domains.[1]

The subjects were first-enlistment airmen who were identified by their first-line supervisors as being either technically proficient or technically deficient in performing their jobs as avionics technician apprentices and jet engine mechanic apprentices. When asked to decompose either a complex electronics system or the engine used in the F-15 aircraft into a hierarchy of components and sub-components, the airmen responded as the expert-novice literature would predict. The proficient performers discussed the systems in terms of their functional properties, making the decompositions based on how the system worked. At the end of the exercise, the knowledge trees that the strong performers produced were rich and well integrated. A sample expert structure is shown in Figure 1. By contrast, the deficient performers discussed the systems in terms of their physical properties, making the decompositions based on how the systems looked. The knowledge nodes they produced typically formed sparse networks of isolated bits of information (see Figure 2).

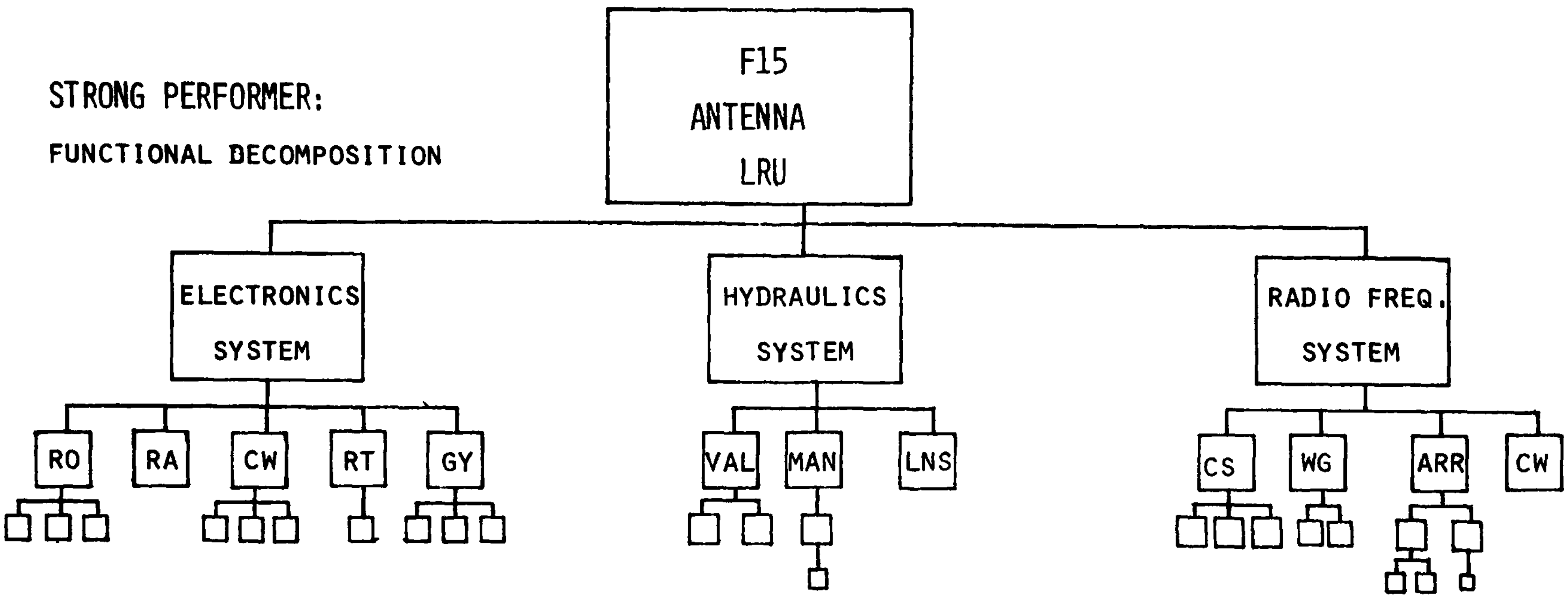
What a finding like this suggests is the importance in apprenticeship of having organized, functionally oriented core knowledge, the type that enables subsequent learning. For some learners it is readily conceivable that such functional job conceptions are not acquired in the natural course of Air Force technical training. Rather, what may very well happen is that a certain proportion of students is unable to make sense out of the substantial amount of technically loaded material to acquire some kind of fundamental understanding of the particular domain. A consequence of this failure is that apprentice airmen may report to the job equipped with little more than labels of surface features to rely upon as knowledge bases. They can name the components of an F-15 antenna system, for example, and perhaps make tenuous, physically oriented interrelationships, but their understanding is limited to the surface features. There is no deeper understanding of the electronic and hydraulic workings of the system, the kind of understanding needed for troubleshooting and repair activities and, perhaps more importantly, for additional learning. Without a basic framework for interpreting the new input encountered on the job, the airman may find additional information to represent only more of the same; that is, more ambiguous technical labels that test the limits of memory and act to swamp information processing capabilities.

So it is that core knowledge can be justified as a basic job skill. In much the same way that reading is viewed as a "power" providing a means to an end, functional core knowledge may be an enabling tool that allows the novice

[1] Data collected under contract No. F41689-83-C-0029 with the University of Pittsburgh, Learning Research and Development Center.

STRONG PERFORMER:

FUNCTIONAL DECOMPOSITION



LEGEND:

ARR - ARRAY
CS - CHANNEL SELECTORS
CW - CABLE WRAPS
GY - GYROS
LNS - LINES
LRU - LINE REPLACEABLE UNIT
MAN - MANIFOLD
RA - ROLL AXIS
RO - READOUTS
RT - ROLL TORQUE
VAL - VALVES
WG - WAVE GUIDES

FIGURE 1. COGNITIVE STRUCTURE DISPLAYED BY STRONG PERFORMER.

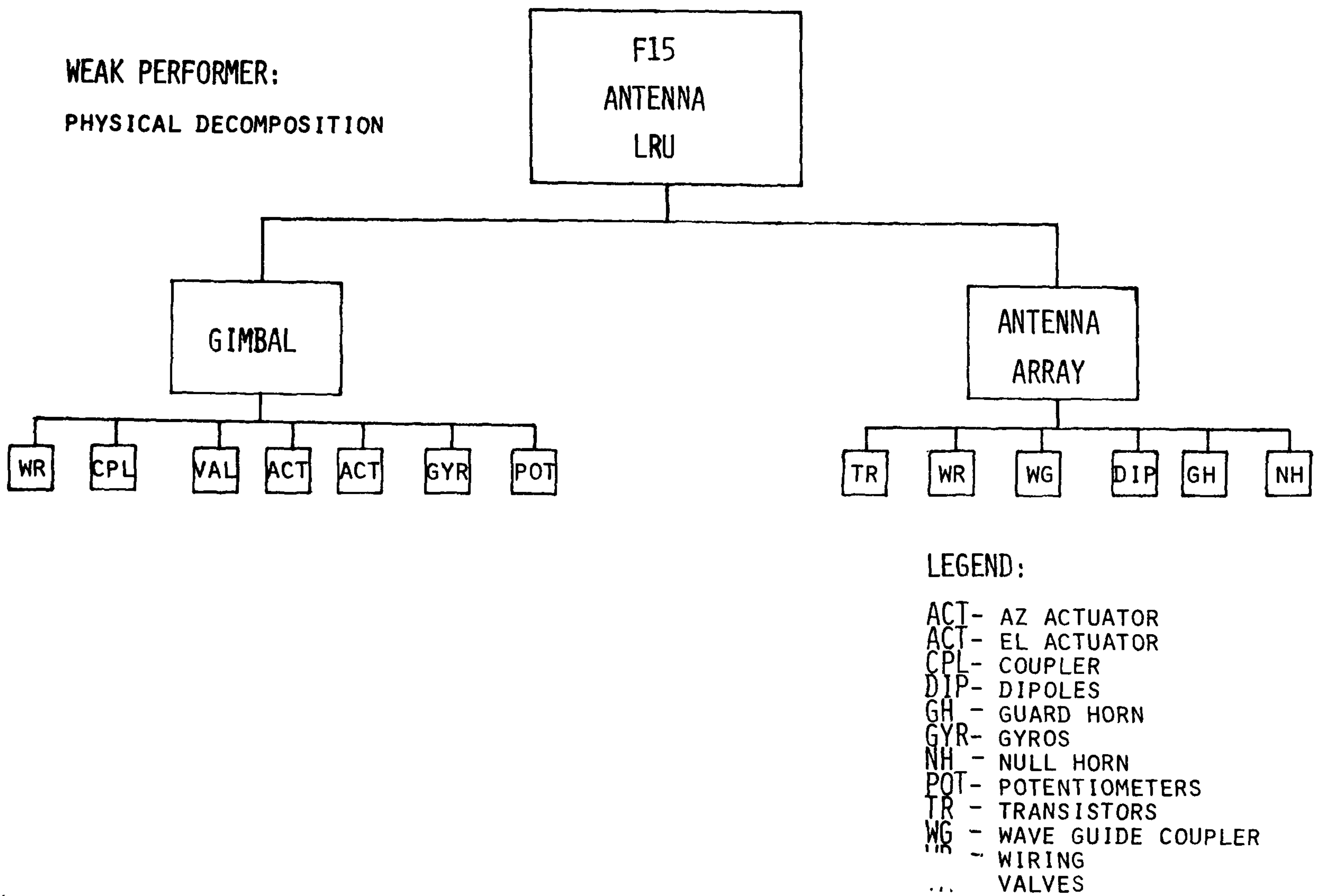


FIGURE 2. COGNITIVE STRUCTURE DISPLAYED BY WEAK PERFORMER.

to make sense out of a complex work environment -- a tool that makes on-the-job learning, apprenticeship proficiency, and skill progression realistically attainable goals.

INSTRUCTION BASED ON COGNITIVE THEORY

To state a convincing rationale for functionally organized core knowledge as a basic job skill is one thing; to build a program of instruction based on cognitive theory with the stated purpose of enhancing core knowledge structures and associated thinking processes is quite another. Instructional technology is being influenced to a greater and greater degree by cognitive principles, however, to the point that there are now sufficient theoretical and empirical studies to provide a sound basis for such an endeavor. Calfee (1981) has drawn upon some theoretical principles from cognitive psychology to comment on curriculum design in a way that is quite relevant to a discussion of novice vs. expert knowledge structures. He emphasized the importance of functionally derived chunks in the process of understanding a complicated structure. Curricula should recognize the limited processing capacities of humans and divide a complicated structure into a relatively small number of chunks -- chunks that are meaningful and coherent so that conscious understanding is facilitated. Perhaps that is a major contribution of cognitive theory and applications; namely, a reestablishing of the importance of conscious understanding in learning. The transfer of learning to novel situations is fostered by a conscious understanding of the principles involved, and deeper knowledge structures are constructed accurately and efficiently if initial conceptions are sound. Some recent empirical research investigating training procedures provides evidence to this effect.

In work sponsored by the Navy, the role of mental models in operating complex devices was examined under various training conditions (Kieras & Bovair, 1983). The objective was to examine the effect of explicitly teaching functionally oriented mental models as part of instruction in the operation of an electrical control device. Comparisons of experimental and control groups revealed that students who were provided an interesting model for explaining the purpose of the device learned operating procedures faster, retained operating procedural knowledge better, and made faster and more direct inferences about the workings of the device than did students who were instructed only in operating procedures and who were provided the device without any functional model. The effect of mental models in the training of electronics troubleshooting, power plant engineering, and x-ray diagnosing skills has also been investigated. In each domain, causal models were incorporated into instruction to enable students to learn how the various systems worked and thus understand how inferences could be made to guide problem-solving strategies (Federation of Behavioral, Psychological, and Cognitive Sciences, 1983). This is in contrast to the more traditional instruction where formulas and computational procedures are explicitly addressed in curriculum, but the conditions of their use are not treated directly. This emphasis on inferencing is judged to be particularly important for workers who engage in troubleshooting activities on large, complex systems, where the sheer number of covarying conditions makes it impossible to treat each malfunction as a special case to be handled by rote procedures. The technician needs a sound general model of the system in order to formulate defensible hypotheses when novel situations are encountered. Training of the type described above has been effective in providing the learner with a mental model to use in simulating "in the mind's eye" how a system is functioning and

thereby formulate reasonable hypotheses about causes of observed malfunctions. It is an all-too-frequent pitfall of technical training programs that causal models are ignored in favor of treating exhaustively, but only descriptively, the myriad components and features of complex systems; all this done in the interest of treating the subject matter "comprehensively." Developers of training programs would be well advised to consider advancements in cognitive science that demonstrate the importance of initial schemata. It now seems clear that more emphasis needs to be given to the development of these initial schemata -- either by ensuring contact with the learner's prior knowledge so that it can be restructured to accommodate the new input or by providing temporary models by which new input can be understood, if individuals lack prior knowledge bases in the domain.

A specific recommendation for instruction in the assembling of complex systems can be taken from other Navy-sponsored work concerned with how individuals understand, execute, remember, and use instructions (Office of Naval Research, 1982). In work addressing the assembly of an electrical circuit, the effects of various forms of instructions were examined. The experimental forms incorporated a hierarchical rationale for each step in the assembly procedures, the premise being that an up-front, higher order explanation of the goals of the steps would aid performance. The rationales were of two types -- structural and functional. Individuals receiving hierarchical explanations with functional information demonstrated superior troubleshooting of faulty circuits and more accurate reconstructing of the original circuit. The combination of reasonable explanations of performance goals and a functional orientation toward the system in question may enable the learner to construct the kind of conscious understanding Calfee (1981) has described. In any event it seems clear that advances in cognitive science are offering to instructional technology some potentially powerful methods for improving instruction, particularly in complex disciplines. In the past, deficient students have simply been recycled through the same curriculum if remediation was prescribed by some diagnostic measure. An instructional program that comes to grips with how understanding can best be achieved in the initial cycle for all students seems to be a worthwhile goal.

CONCLUSION

An appeal was recently made to the effect that "education for technology must become a concern of our educational process" (Federation of Behavioral, Psychological, and Cognitive Sciences, 1983, p. 26). The basis for the appeal was the recognition of the growing role of technology in human affairs, a condition that poses the challenge of educating students at all stages of their development to understand and to use technological resources. As the developer of a particular type of adult education program, the Air Force views the challenge of delivering technology-rooted instruction as quite consistent with meeting the demands that airmen are presently facing and will no doubt continue to face in the workplace. A particularly promising instructional objective for such a training program is the constructing of functional mental conceptions that enable the learner to interpret complex systems and phenomena meaningfully and simultaneously to advance knowledge. Such knowledge conceptions may well boost educational processes for technology beyond the stage of development that processing "powers" such as reading and computing have been able to achieve in the past.

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